Interactive Realistic Simulation of Wireless Networks

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ABSTRACT

Ray tracing is the core technology that enables the physically correct simulation of light transport. Much progress has been made to increase the efficiency of the basic algorithm and it lends itself to simulations outside the domain of computer graphics. We explore current ray tracing technology to simulate wireless networks at interactive rates. Other than in classic computer graphics diffraction contributes important parts of the solution, but is difficult to capture. We present a ray tracing based algorithm that outperforms state of the art simulation technology by far, as verified by a real-world experiment.

1 INTRODUCTION

Communication between vehicles is one way to improve both safety and efficiency of road traffic. Therefore self-organizing networks, so-called Vehicular Ad-Hoc Networks (VANETs), are a very active area of research. In order to evaluate solutions, the scalability of varying routing algorithms, aspects of communication security, and data aggregation to reduce the communication complexity need to be studied.

Like for many other mobile networks, most of this research is done using network simulators. Simulations offer an exact reproducibility and allow a better analysis of the influence of single parameters than an experiment can do. In addition simulations allow one to easily modify parameters like e.g. speed, movement model, and traffic load at much lower cost and higher safety as compared to real-world experiments.

However, most of today's network simulators oversimplify the reality especially in one aspect: The effects of the propagation of radio signals, which can be seen as the foundation of mobile communication, are calculated using the free-space path-loss model, which only uses attenuation by the distance of sender and receiver and ignores blockers.

While this assumption can be used for a rough prediction of signal behavior in a plain and open countryside environment, it totally fails in inner-city scenarios as the buildings' effects on the signal are neglected. This is shown in Figure 2 which compares real-world measurements of signal power in a typical inner-city environment to the predictions made by the free-space calculation as it is done by the state-of-the-art mobile network simulators.

Simulating mobile networks means that we have to handle several hundred thousands of communication events during one average-size simulation run. For each communication event a new call to the propagation simulator has to be made. As the communication results might influence the behavior to the mobile nodes (e.g. making vehicles driving around traffic jams after the vehicle received information about the traffic jam), this requires a very high level of interactivity between the network simulator and the propagation simulator. Both the sender and receiver are mobile and their positions are constantly changing and are unpredictable, which is a huge difference to e.g. cellular networks. In our case, pre-calculation as suggested by some of the related work is not really feasible.

In this paper we present an improvement for mobile network simulators based on ray tracing [7, 13]. Ray tracing as known from computer graphics will be used to estimate the loss of signal power on the signal's way from sender to receiver by conceiving the radio signal as optical light enhanced by the consideration of wavelength specific effects like diffraction at edges. The ray tracer's results are then used to decide whether a destination node was able to receive the transmitted information successfully or not. The high precision of our algorithm has been verified by a real-world experiment.

2 COMMUNICATION WITH RADIO WAVES

Both radio waves and light are electromagnetic waves. Although both follow the same physical laws in principle, the strength of the effects depends on the wavelength. The radio waves, which have been considered in this work, have a frequency of 2.4 GHz as used in the IEEE 802.11b/g standard. This frequency results in a wavelength of about $1.25 \cdot 10^{-1} m$, whereas the wavelength of optical light is between 3.8 and $7.5 \cdot 10^{-7} m$.

As expected, the difference of about six orders of magnitude lets the radio waves behave differently from visible light when interacting with matter. Opposite to computer graphics, in radio ray tracing

- diffuse reflection can be neglected as specular reflection is the dominant effect, and
- diffraction cannot be neglected due to the longer wavelengths.

This section's purpose is to sketch the physical basics of communication by using radio waves.

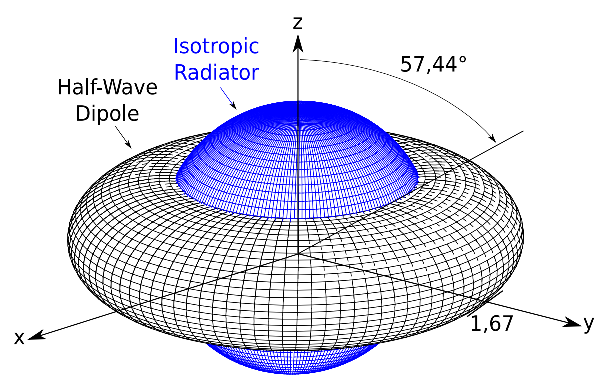

Figure 1: Direction-dependent gain of a half-wave dipole antenna (Equation 1) as compared to the ideal isotropic radiator: Between an angle of $0°$ and $57.44°$ the half-wave dipole's radiation is weaker than the one of an ideal isotropic radiator and higher between $57.44°$ and $122.56°$. At $90°$ the half-wave dipole reaches its maximum gain and radiates 1.67 times as much power as an equally supplied isotropic radiator would do.

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2.1 Sending and Receiving Radio Waves

One of the most important components of wireless communication are antennas. They are used to send out and receive radio signals. Antennas differ widely in their shape, which leads to very different antenna types each having its own radiation characteristic. Other than an ideal point-shaped antenna (a.k.a. isotropic radiator), the power distribution of a real antenna is not isotropic.

For our simulation we will use a half-wave dipole antenna with the characteristic

$$G(\phi) = 1.67 \cdot \left[\frac{\cos\left(\frac{\pi}{2} \cdot \cos\phi\right)}{\sin\phi} \right]^2 \tag{1}$$

as a function of the azimuth angle ϕ (see figure 1 for a visualization). Obviously the anisotropic characteristics of an antenna have to be considered in a simulation.

2.2 Attenuation in Free-Space

In free space a point source will send out three-dimensional spherical waves. It is then appropriate to use geometric optics, where electromagnetic waves are understood as ray fronts. The whole concept of ray tracing is based on this assumption.

The intensity (power per area) of a point source decreases proportional to the inverse square law in the distance r between transmitter and receiver as the emitted power diverges into space. This is also called free-space path-loss since it occurs without the presence of any matter:

$$P_{receiver}(r) = P_{transmitter} \cdot \frac{1}{4\pi r^2} \tag{2}$$

2.3 Interaction with Matter

Whenever electromagnetic radiation comes across matter, they interact in some way (changes can happen to direction, amplitude, phase and the wavelength). The kind and intensity of interactions vary widely depending on mainly two factors: The wavelength and the material that is hit by the wave. The following sections will give a short overview of the physical effects of wave-matter interactions that can occur and must be considered in order to improve the quality of simulation.

2.3.1 Refraction

If an electromagnetic wave hits the surface of a material, some parts of it migrate into and eventually *transmit* through the material. Thereby the direction of the wavefront is changed according to Snell's Law of *Refraction*. The presence of matter is not only able to change the direction of the wavefront, but also absorbs some of its power, i.e. the wave becomes *attenuated*.

Attenuation and refraction are highly dependent on the electromagnetic properties of the matter, especially on the matter's permeability and permittivity. The Fresnel equations as given in [5] can be used to compute the refracted part of the wave.

In our radio ray tracer these effects were neglected, because in our present stage of extension the only kind of obstacles that we consider in our models are buildings. As only outdoor scenarios are modeled in our scope, signal propagation through walls of buildings would be only of interest when considering waves that propagate completely through buildings. However this effect is very difficult to model as it relies a lot on the buildings' interior geometry and materials, but would also imply to consider additional radio noise generated within the buildings, e.g. by interior wireless networks. Additionally, the resulting energy after transmission through a building would be very low and is therefore also neglected in other publications [10]. This means that buildings can be modeled completely opaque to radio waves.

Refraction and attenuation are not only caused by solid matter like walls, but also by the atmosphere and its contents, for example nitrogen, oxygen on the one hand and water, as well in dissolved as in condensed state. Atmospheric effects on radio waves are definitively measurable, for example in long wave propagation. For wireless LANs attenuation due to atmospheric effects is not of great importance: According to [4], moderate rain ($\approx 5\ \frac{mm}{h}$) causes an attenuation of $0.074\frac{dB}{km}$ at a frequency of 10 GHz, which is even weaker at lower frequencies. Although oxygen absorbs energy in the microwave region, the attenuation caused by this effect is less than $\approx 10^{-2}\ \frac{dB}{km}$ according to [4]. For water vapor an attenuation of about $10^{-3}\ \frac{dB}{km}$ is given. Due to the typical range of wireless LAN (about 200 up to 500 meters in the free space when using omnidirectional antennas) these effects were neglected in the scope of this work.

2.3.2 Specular Reflection

Not all parts of an electromagnetic wave will move into a material, but some of the wave's energy is reflected at the surface. This effect is well-known from optics, for example when light hits a mirror or the surface of water. The angle between the reflected wave and the normal vector of the reflecting surface is the same as the one between the incoming wave and the normal. Again, Fresnel equations are used to describe the reflected part.

In our radio ray tracer the specular reflection is the most relevant effect. All parts of energy that are not absorbed by the buildings are reflected in that way.

2.3.3 Diffuse Reflection and Scattering

Diffuse reflection or scattering is based on the same physical phenomenon as specular reflection. Depending on the roughness of an optical interface and the wavelength of the incoming wave, a certain fraction of the wave does not get reflected in a specular way, but is scattered into arbitrary directions.

In [10] the relation between the specular and the diffuse proportion of reflection

$$R^{mod}_{\parallel,\perp} = R_{\parallel,\perp} \cdot e^{-8\pi^2\left(\frac{\sigma_h}{\lambda}\right)^2 \cdot \cos^2\alpha} \tag{3}$$

is given as a modification to the Fresnel equations. $\frac{\sigma_h}{\lambda}$ is the ratio of the material's roughness σ_h and wavelength λ, α the angle of the incoming rays to the surface normal and $R_{\parallel,\perp}$ the material- and angle-dependent Fresnel coefficient, that represents the reflected proportion.

$R^{mod}_{\parallel,\perp}$ finally represents the proportion that is reflected in a specular way. It follows that the difference between $R_{\parallel,\perp}$ and $R^{mod}_{\parallel,\perp}$ is that part of energy, which is scattered.

The equation models an every-day experience: On the one hand, it shows that when dealing with visible light (very short waves), most of the surfaces -besides very smooth ones, like mirrors- show a remarkable portion of diffuse reflection, as they are coarse compared to the wavelength of light. On the other hand, the much longer radio waves will be scattered only when hitting rough objects, for example plants and trees. Studying the equation with varying material parameters shows that when dealing with an ideal form of box-shaped buildings consisting of concrete, only specular reflection is of real importance. For a wavelength of $1.25 \cdot 10^{-1}m$ and a roughness of $\sigma_h = 1\ mm$ (see: [10]) the term $e^{-8\pi^2\left(\frac{\sigma_h}{\lambda}\right)\cdot\cos^2\alpha}$ ranges between 0.995 and 1 (for all possible values of α).

In our radio ray tracer diffuse reflection has been neglected up to now, but must be implemented to model more complex scenarios. That means, in the presented results the value of $R^{mod}_{\parallel,\perp}$ equals to $R_{\parallel,\perp}$, i.e. to the complete part of the reflected energy according to the Fresnel coefficient.

2.3.4 Diffraction

Diffraction is a physical phenomenon that cannot be explained by geometrical optics. To understand it, the Huygens-Fresnel principle [16] can be used. Diffraction means that electromagnetic waves can also propagate into actually shadowed areas, for example, around the corners of a building.

For the scope of our work, effects of diffraction are only of interest at the edges of buildings.

According to [10] the amount of energy that gets diffracted depends on the wavelength. The longer the involved waves are, the more effects of diffraction are of importance. This is the reason why it is very uncommon to recognize effects of diffraction in day-to-day's optics and why the geometrical optics are sufficient to explain the propagation of visible light. Therefore diffraction is usually neglected in optical ray tracing.

The most popular models to enhance the geometrical optics by effects of diffraction are the Geometrical Theory of Diffraction (GTD, see [9]) and the Heisenberg Uncertainty Ray Bending (HURB, see [6]).

A simplified form of GTD is described in [1] in combination with audio ray tracing. There is a simple cosine-relation given that describes the weighting of the intensity of diffracted waves according to the angle that they got diffracted. This leads to

$$f(\phi) = \begin{cases} \frac{\cos\left(\frac{4}{3}\phi\right)+1}{2} & 0^\circ <= \phi <= 135^\circ \\ 0 & \phi > 135^\circ \end{cases} \tag{4}$$

2.4 Signal Reconstruction

As it is the receiver's task is to reconstruct data out of the received electrical signal, the last step after following signals on their ways from sender to receiver is to simulate the signal reconstruction at the receiver's site. Therefore a decision has to be made, whether the receiver is able to decode the information out of a signal or not. To put it simple, decoding a received signal is possible, whenever the ratio of signal power and the power of noise is above a certain value. This value depends on the quality of the receiver.

Due to interference, signal reconstruction in a wireless network can be more difficult than in computer graphics:

Multi-Path Propagation and Interference. Due to the various types of possible interaction between waves and matter, there are a lot of potential radio paths between sender and receiver for the signal to propagate. Each path has its individual length and each part of the signal will undergo influences by the path. This leads to a superposition of waves at the receiver, which can either be destructive or constructive depending on the phase difference.

To calculate the resulting power at the receiver antenna, the amplitudes and phases transported along a ray are summarized separately.

Multiple Simultaneous Senders. A typical VANET scenario consists of several nodes (e.g. cars) that constitute one network and share one radio frequency. So it is obvious that more than one sender may be active at one point in time. As one receiver is only able to gather information from exactly one sender at each moment, the other nodes that are sending at the same time and are close enough to the receiver will contribute to the radio channel's noise. This relates to the multiple lights problem in computer graphics.

3 Radio Ray Tracing Algorithm

In this section we introduce our ray tracing algorithm, which has been used to simulate the propagation of radio signals based on the effects described in the previous section.

As mentioned before, the propagation of radio waves does not differ in principle from optics, however, diffraction has to be considered. Therefore the principle idea was to use ray tracing as known from optics, but enhance it mainly by diffraction effects at edges of buildings, adapt the weighting functions to radio communication, and integrate it into a network simulator.

The general approach is to estimate if the sender is "visible" from the receiver's position by path tracing [8, 13]:

- The first step is to estimate whether a direct line of sight between receiver and sender exists. If so, its parameters (distance, angle of emission and reception at both antennas) are known. This connection is added to a data structure which stores the paths between sender and receiver.

- In the next step, indirect paths between sender and receiver have to be estimated. Therefore, we generate primary rays with the receivers position as the origin. As their directions we generate vectors through a spherical grid that is positioned virtually around the receiver antenna. For each of these rays interaction with matter (e.g. buildings) is explored by tracing it into the scene [17]. Whenever a primary ray hits an object, a new point of interaction is generated and the parameters (length, angles) of the primary ray are stored temporarily.
  - For each point of intersection it is checked, whether the sender is visible from this point. If so, the angle of incidence and the normal to the object's surface is calculated. As diffuse scattering can be neglected (for now), only the dominant specular component
  $$I_{specular}(\phi) = I_{incident} \cdot R^{mod}_{\parallel,\perp} \cdot \cos^n \phi \tag{5}$$
  is calculated to weight the incident power.
  - In the next step a secondary ray according to the law of specular reflection is generated and the whole algorithm is called recursively.

  The contribution of a transport path is computed using Friis' Transmission Formula (deduced in [2])
  $$I_{Receiver}(r,\lambda) = I_{Incident} \cdot G_{Receiver} \cdot \left(\frac{\lambda}{4\pi r}\right)^2 \tag{6}$$
  for the primary ray segments, where λ represents the wavelength, $G_{Receiver}$ is the antenna gain of the receiver antenna, and r is the length of the ray segment. The intensity $I_{Incident}$ then is determined by evaluating Equation (5) recursively and attenuating with the inverse square law given in Equation (2). The last segment is similar to the first and contributes
  $$I_{Incident\ at\ point\ of\ intersection}(r,\lambda) = I_{Sender} \cdot G_{Sender} \cdot \left(\frac{\lambda}{4\pi r}\right)^2,$$
  where I_{Sender} represents the power of the sending antenna, and G_{Sender} is the sender's antenna gain. Note that in our simulation antenna gains of both, sender and receiver, are modeled as half-wave dipole antenna as given by Equation (1).

3.1 Approximate Diffraction

Contrary to optical ray tracers we have to deal with effects of diffraction. In order to determine the contribution of diffraction to a vertex of the path, we send rays through regular grid points mapped onto the unit sphere and perform the following checks:

- If neighboring rays hit the same object and normals points into the same direction, no edge is detected. The same happens if not objects are hit.

- Otherwise an edge is found and needs to be located more precisely. Therefore the regular grid is adaptively refined (similar to adaptive oversampling as in [7]).

The detected points closest to the edges are treated as new points of interaction. Their contribution is computed by recursively calling the procedure of the previous section and weighted according to Equation (4). As we will validate in Section 4, this simple algorithm captures diffraction at high precision.

As long as buildings are just modeled as boxes, there would be more direct ways of locating their edges. On the other hand, the sampling based method is also able to support scenes containing more complicated objects that might be composed of triangles.

3.2 Implementation

For efficient ray tracing we used the bounding interval hierarchy [17]. The algorithm is very simple to implement and provides a rapid construction procedure, which is crucial, since we want to consider dynamic scenarios with moving objects.

In order to improve the performance further, we cache evaluations in a spatial regular grid. So instead of calling the radio ray tracer, recently computed values can be used, if they are close enough the location, where an evaluation is required. As soon as cars will be considered, the spatial caching has to be switched off.

The recursion depth for finding diffracted paths has been set to one diffraction per propagation path as a trade-off between runtime and accuracy (see Table 1).

4 Experimental Validation

In order to verify the precision of our algorithm, we compared the simulation results to real-world measurements.

4.1 Setup

We decided to run the experiment in a typical urban area, as we expected the most significant deviations from standard simulator behavior there. Furthermore, this scenario is also significant for our work on vehicular networks.

4.1.1 Choosing an Appropriate Test Area

A part of an inner city (shown in Figure 3, dimension about 220×250 square meters) was chosen as an area for the validation. This area allows for building a correct model in the computer:

- The terrain is flat, which simplifies modeling.
- As cars influence the propagation of radio waves, an area with low traffic and a small number of parking cars was chosen to avoid the modeling of cars.
- As the scattering effects of e.g. plants have not been implemented yet, we chose an area which has mostly buildings and almost no gardens or other plantings in its vicinity.
- The houses should not be too difficult to model. In the selected area, we have mostly planar surfaces and box houses.

4.1.2 Modeling the Test Area

The next step was to model the selected test area and render the radio propagation with our ray tracer to get radio maps of the area for varying sender positions. One of the resulting maps is shown in Figure 4. This was done in advance in order to identify interesting points for the real-world measurements.

The blocks of houses were simply modeled as boxes with a fixed height of 15 m. For the surface properties of concrete, the values given in the appendix of [10] have been used. All buildings were modeled with the same surface properties.

Table 1 summarizes the parameters of the simulation. The parameters for power, frequency, height, and antenna type and length where chosen to fit the technical data of the wireless LAN equipment we used for validation. The sampling rates of 0.5° (i.e. primary rays were emitted in angles of 0.5°) and the recursions were a trade-off between computation time and accuracy.

Sender power	100 mW (= 20 dBm)
Sender frequency	2.4 GHz
Sender: Height above ground	1.5 m
Receiver: Height above ground	1.5 m
Sampling rate: Azimuth	0.5°
Sampling rate: Elevation	0.5°
Antenna type	Half-wave dipole
Antenna length	6 cm
Recursion depth (Reflections)	5
Recursion depth (Diffraction)	1

Table 1: Parameters used to simulate the map shown in figure 4.

The calculated map in Figure 4 shows the same area as the aerial view on the left with signal power shown in false colors. The image shows a slice of the 3D radio map at the altitude of the sender and receiver antennas. However, all rendering is done in 3D and different antenna altitudes are of course supported.

After selecting several interesting receiver positions (e.g. very close but without direct line of sight to the sender due to buildings), we were prepared for real world measurements.

4.1.3 Measurement

We used two notebooks, each connected to an external half-wave dipole antenna with similar antenna characteristics like the one used in the simulation. As wireless LAN standard, IEEE 802.11 b was used.

One notebook was placed fix at the selected sender's position (red mark in Figure 3). The other one was moved to the 17 positions marked in the map to act as receiver. While the sender was constantly transmitting beacons at a rate of one Hertz, we sampled the signal strength at the receiver for 30 seconds at each position and later averaged the results to reduce artifacts that might have been caused by short term fading.

Measurements at position REF have been done for reference purpose: Sender and receiver antennas were both placed with only one meter of distance between them in a direct line of sight.

4.2 Results

The results of the experiment are visualized in Figure 2 and are compared to the ray tracing based calculations that were used to create the propagation map and also to the values calculated with the free-space model normally implemented by mobile network simulators (we used JiST/SWANS [3] as reference).

Figure 2 clearly shows that the free-space model overestimates the signal power significantly for all the tested positions. Additionally, you can see that the free-space model has a rather smooth curve whereas in reality the received signal strength varies significantly even for adjacent positions.

4.3 Discussion

Thus the obvious assumption has been affirmed: A propagation model that relies only on the distance between sender and receiver might be sufficient to model mobile networks in large free-space environments with a direct line of sight between sender and receiver. However, in urban scenarios at least the effects caused by buildings need to be taken into account. Our implemented model shows that considering additional effects like blocking, specular reflection, and diffraction gives already a very close approximation of the real-world.

On the other hand, the effects of scattering seem to be not too significant, at least in simple scenarios like the one we studied. In different scenarios with a lot of vegetation, this might however change completely.

5 Related Work

The problem of unrealistic radio probability models in the simulation of VANETs has also been acknowledged by other authors, like e.g. being described in [11]. However, the authors simply apply a probabilistic shadowing model which uses a Gaussian distributed random variable to model short-term fading effects like created by multi-path propagation. Of course this approach has huge advantages when it comes to performance, however it is nearly useless when e.g. modeling situations at intersections where houses block direct connectivity between cars approaching the intersection from different streets.

On the other hand, there is extensive work on ray-tracing-based coverage prediction techniques for networks with static base stations, like it is the case e.g. in GSM or UMTS networks. [19] presents some early ideas on this subject.

Other work builds on top of this and uses the pre-calculated results for their later simulations. [15, 12] are examples. Based on how extensive the pre-calculation of the scene and occurring radio-communications is done, this might offer significant performance advantages. The pre-calculation needs to consider each possible combination of sender and receiver position and uses a grid to discretize the positions. This approach has the advantage that tools known from cellular network planing can be used as demonstrated in [15]. These tools contain a lot of experience in the physics of radio waves. But there are some fundamental limitations when using pre-calculations. It is e.g. impossible to add radio propagation effects caused by moving vehicles, as the position of the cars is unknown at the time the radio propagation is calculated but needs to be considered e.g. for shadowing or reflection effects.

This drawback is addressed in [14] which creates trace files in the first step, i.e. files that contain a description how each of the vehicles travels. In a second step these trace files are used to simulate radio propagation using a ray tracing method. In the third step, the actual network simulation is done. Although this design allows to simulate the influence of vehicles to radio propagation, it is not suited for our goal as well. Many VANET applications are warning applications, i.e. the driver gets displayed warning messages based on the information that the vehicle receives via wireless communication. The driver is then expected to change his behavior and e.g. brake, adapt speed, or take an alternative route.

Using the approach in [14], it is hardly possible to do such simulations, as all movements need to be previously known before the radio propagation and communication is simulated. Therefore we think that static pre-calculations cannot be applied for simulations of all kinds of dynamic and mobile application scenarios. Instead an online simulation is needed like presented in this paper. Performance optimizations like the ones used in interactive ray-tracing and caching approaches can then be used to enhance speed.

As urban environment can sometimes be modeled by very simple scenes consisting mainly of rectangular blocks or other simple geometric primitives, this can be used to speed up ray-tracing. The work presented in [20, 22] presents some examples how this can be done. The same group has also done some experiments that compare the ray-tracing predictions to real-world measurements [21] based on data that was gathered as part of the COST 231 project. This might serve as a basis for our further activities to simulate more complex VANET scenarios.

6 Conclusion

With our simple simulation algorithm we are already able to match measured data very precisely although still some effects have been neglected. It is obvious that much of the simulation results for mobile networks done using free-space models have at least to be questioned, because the connectivity is strongly overestimated and therefore, e.g. routing protocols behave better in simulations than they do in the real world.

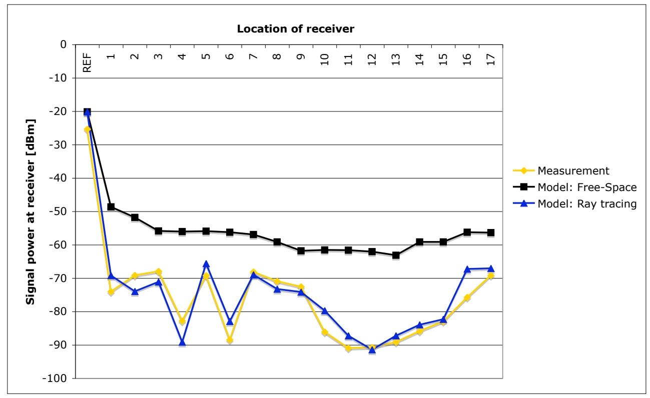

Figure 2: Experimental validation: State-of-the-art methods of VANET simulators overestimate the signal level in urban areas as they completely ignore buildings. Considering blockers and thus diffraction increases precision dramatically, as with only a crude approximation of the buildings the prediction by our ray tracing algorithm almost coincides with the measurement.

At the same time, we have to admit that the performance of our algorithm can be improved further: We did not include the latest improvements of tracing packets of rays (see e.g. [18] and the vast amount of follow-up literature initiated by the thesis). This will pay off especially when sending out sets of rays for searching the edges of buildings in order to simulate diffraction.

We are convinced that including scattering and moving vehicles will result in an even improved precision. This is a goal of our ongoing work, which will also allow us to run similar real-world experiments like the one presented in more complex scenarios.

Using our ray tracing radio model we plan to reproduce some of the analysis done for vehicular networks so far and compare the suitability of different protocols. We expect that some protocols like position-based routing could behave worse than assumed so far.

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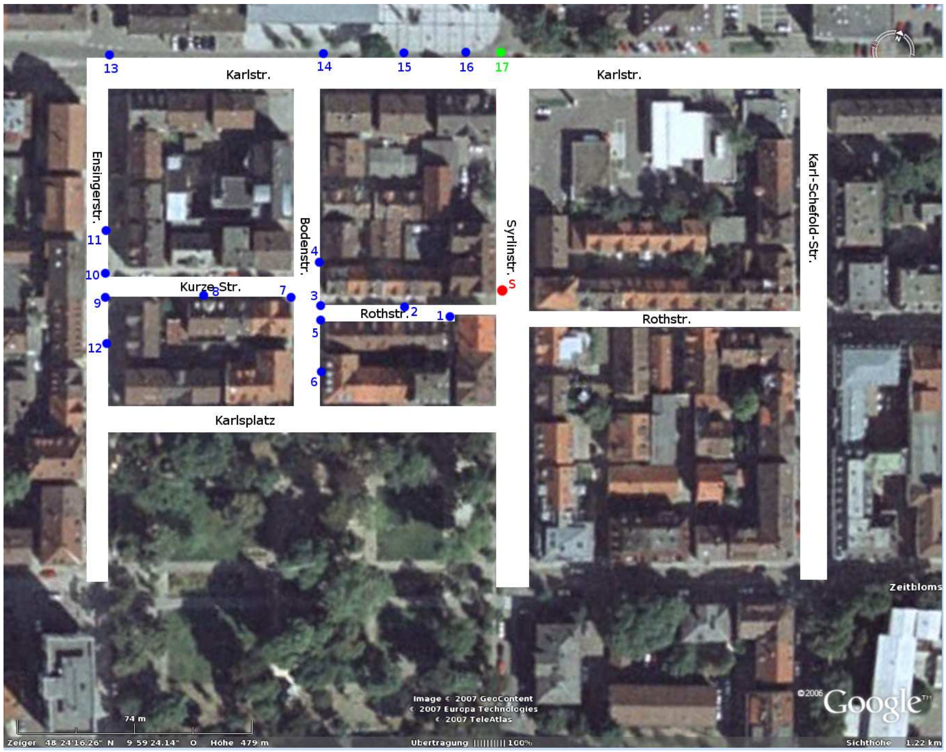

Figure 3: Experimental setup: Ulm city, where the measurements were taken at the numbered blue points. The sender is located in the red point.

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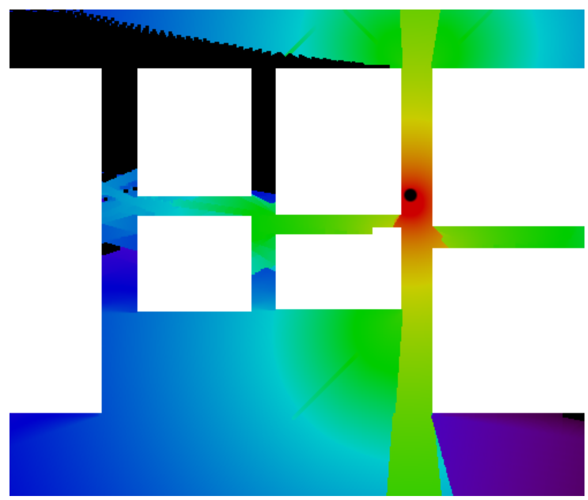

Figure 4: For the simulation buildings were modeled as cuboids. The false colors visualize the simulated path-loss (from red = small to blue = large).